



- (51) **International Patent Classification:**
H04B 10/13 (2006.01) *H04J 14/02* (2006.01)
- (21) **International Application Number:**
PCT/US2012/036255
- (22) **International Filing Date:**
3 May 2012 (03.05.2012)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
61/482,547 4 May 2011 (04.05.2011) US
- (71) **Applicant (for all designated States except US):** **BOARD OF REGENTS, UNIVERSITY OF TEXAS SYSTEM** [US/US]; 201 West 7th Street, Austin, Texas 78701 (US).
- (72) **Inventors; and**
- (75) **Inventors/Applicants (for US only):** **VISHWANATH, Sriram** [US/US]; 2607 Euclid Avenue, Austin, Texas 78704 (US). **BANK, Seth R.** [US/US]; 1501 Nickerson Street, Austin, Texas 78704 (US). **APPAIAH, Kumar** [IN/US]; 1507 Houston Street, #242, Austin, Texas 78756 (US).
- (74) **Agent:** **MUNYON, Dean, M.**; Meyertons, Hood, Kivlin, Kowert & Goetzel, P.O. Box 398, Austin, Texas 78746 (US).
- (81) **Designated States (unless otherwise indicated, for every kind of national protection available):** AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States (unless otherwise indicated, for every kind of regional protection available):** ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

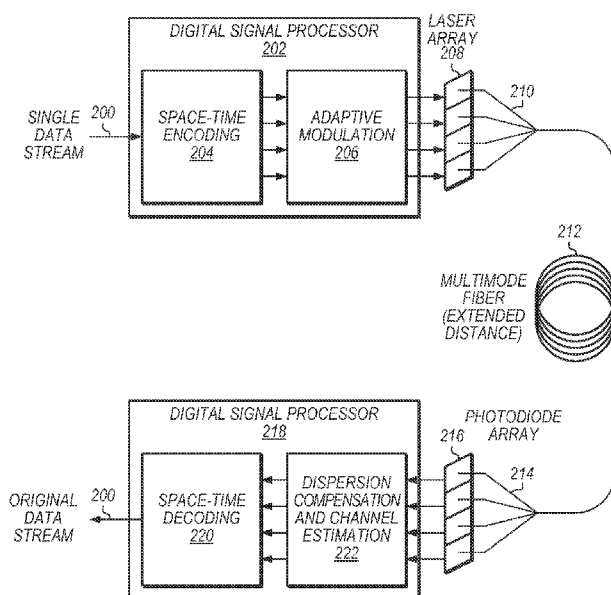
(54) **Title:** METHODS AND APPARATUS FOR LONG-DISTANCE TRANSMISSION ACROSS MULTI-MODE FIBERS

FIG. 2

(57) **Abstract:** Various method and apparatus embodiments that implement multi-input, multi-output (MIMO) techniques in optical communications systems that utilize multi-mode optical fiber are disclosed. The techniques may include dispersion compensation, adaptive modulation, and optimization of modal coupling diversity. Using these techniques may increase the performance (in terms distance and/or bandwidth) of optical communications systems based on multi-mode fibers.



Published:

- *without international search report and to be republished
upon receipt of that report (Rule 48.2(g))*

TITLE: METHODS AND APPARATUS FOR LONG-DISTANCE TRANSMISSION ACROSS MULTI-MODE FIBERSTechnical Field

[0001] This invention relates to optical communications systems, and more particularly, to optical communications systems utilizing multi-mode fiber.

Description of the Related Art

[0002] Optical communications systems may employ one of two types of optical fibers for the transmission of data. A first of these types is single mode optical fiber. Single mode optical fibers are those fibers designed to carry only a single ray of light (mode). Communications systems may use single mode optical fibers for long distance links (e.g, hundreds, if not thousands of kilometers), as such fibers may perform effectively at retaining the fidelity of a transmitted light pulse. One particular application of signal mode optical fibers is in dense wavelength division multiplexing (DWDM) communications systems, which may provide high bandwidth when utilizing single mode optical fibers along with high-precision transmitters and receivers.

[0003] A second type of optical fiber that may be utilized in optical communications systems is multi-mode optical fiber. A mutli-mode optical fiber may carry multiple modes. Multi-mode optical fibers typically have a large core size and a high light gathering capacity. Communications system may employ multi-mode fibers for short distance links (e.g., a few hundred to a few thousand meters), such as links within a single building or between buildings within a complex such as a college campus. Due to their high light gathering capacity, low precision transmitters and receivers may be used in communications systems that utilize multi-mode fibers.

SUMMARY

[0004] Various method and apparatus embodiments that implement multi-input, multi-output (MIMO) techniques in optical communications systems that utilize mutli-mode optical fiber are disclosed. The techniques may include dispersion compensation, adaptive modulation, and optimization of modal coupling diversity. Using these techniques may increase the performance (in terms distance and/or bandwidth) of optical communications systems based on multi-mode fibers.

[0005] In one embodiment, an optical communications system includes a digital signal processor that performs space-time encoding of a data stream prior to the transmission of optical signals onto a multi-mode optical fiber. On the receive side, received optical signals are converted into electrical signals which are then provided to another digital signal processor. The digital signal processor on the receive side may perform dispersion compensation based on estimated channel characteristics. Subsequent to performing the dispersion compensation, space-time decoding may be performed to recover the original data stream.

[0006] In another embodiment, an optical communications system includes a digital signal processor that performs adaptive modulation, on the transmit side, prior to the transmission of optical signals onto a multi-mode fiber. Adaptive modulation may be performed to account for channel characteristics such as temperature and micro-vibration effects. Information indicative of the channel characteristics may be conveyed to the digital signal processor on the transmit side from the receive side via another communications link (e.g., another fiber-optic link). The digital signal processor may use the information indicative of the channel characteristics to more closely match the modulation of the signals to be transmit to the characteristics of the channel upon which they are transmitted.

[0007] In yet another embodiment, an optical communications system may utilize available optoelectronic capacity to optimize modal coupling diversity. The optimization may be performed in such a manner to ensure that a transceiver does not exceed its thermal budget. In one case, a static thermal design power value may be allotted to an array of lasers or other optical transmission devices. In another case, transceiver temperatures may be measured and a portion of an available thermal budget may be allotted to the optical transmission devices. In either case, a number of optical transmission devices that may be operated without exceeding the thermal budget is then calculated. Modal coupling characteristics may be measured at a receiver based on transmissions from each of the optical transmission devices. A set of the optical transmission devices having a maximum modal coupling diversity may then be selected, and communications may subsequently be performed using the devices of the selected set.

[0008] Embodiments may be implemented using as few as one of the techniques described above. Furthermore, embodiments that implement all of the techniques described above may also be implemented. Using these various techniques may enable the implementation of optical communications systems at costs comparable to other optical communications systems that utilize multi-mode fibers while achieving bandwidth and distance associated with more expensive optical communications systems based on single-mode fibers.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Other aspects of the disclosure will become apparent upon reading the following detailed description and upon reference to the accompanying drawings in which:

[0010] FIG. 1 (prior art) is a block diagram of a prior art optical communications system;

[0011] FIG. 2 is a block diagram of one embodiment of an optical communications system;

[0012] FIG. 3 is a block diagram of one embodiment of an optical communications system utilizing adaptive modulation;

[0013] FIG. 4 is a flow diagram of one embodiment of a method for optimizing modal coupling diversity using a dynamically-calculated thermal design power (TDP);

[0014] FIG. 5 is a flow diagram of an embodiment for optimizing modal coupling diversity using a statically-calculated thermal design power (TDP);

[0015] FIGS. 6A, 6B, and 6C are representations of an aspect of an embodiment of an optical communications system that has been optimized for TDP and modal coupling diversity;

[0016] FIGS. 7A, 7B, and 7C are further representations of an aspect of an embodiment of an optical communications system that has been optimized for TDP and modal coupling diversity;

[0017] FIG. 8 is another representation of an aspect of an embodiment of an optical communications system that has been optimized for modal coupling diversity.

DETAILED DESCRIPTION

[0018] The present disclosure is directed toward optical communications systems that use multiple input, multiple output (MIMO) techniques with multi-mode optical fibers in order to increase transmission distances and/or available bandwidths. Prior art optical communications systems based on multi-mode fibers, such as that shown in Fig. 1, are limited in bandwidth and transmission distance relative to systems utilizing single mode fiber. For example, at a transmission rate of 100 Mbit/s, optical communications systems utilizing multi-mode fibers are limited in distance to about 2 kilometers (KM). Higher bandwidths of up to 10 Gbit/s are achievable, but distances are limited to approximately 300 meters. Optical communications systems utilizing single mode fiber may exceed both the distances and available bandwidth over their multi-mode fiber counterparts by significant amounts. However, the implementation costs of optical communications systems based on multi-mode fiber are significantly less than those based on single mode fiber. The various embodiments of an optical communications system to be discussed below utilize various MIMO techniques to increase the distance and/or bandwidth at which multi-mode fiber optical communications systems may operate while maintaining their cost advantages relative to systems based on single mode fiber. Whereas the prior art systems based on multi-mode fiber are limited in distance of up to 2 KM, or bandwidth up to 10 Gbit/s, the systems to be discussed below may exceed one or both of these values.

[0019] The techniques employed by the various embodiments described herein include dispersion compensation, adaptive modulation, and the optimization of modal coupling diversity. Optical communications systems employing one of these techniques are possible and contemplated, as well as those employing two or more of these techniques.

[0020] Fig. 2 is a block diagram of one embodiment of an optical communications system. The system shown in Fig. 2 includes a first digital signal processor (DSP) 202 coupled to an array of optical transmission devices (an array of lasers 208 in this case) that convert electrical signals into optical signals. The system further includes a second DSP 218 including an array of optical-to-electrical (OE) converters (photodiode array 216 in this case) that convert received optical signals into electrical signals. A multi-mode fiber 212 of an extended distance (e.g., greater than 2 KM) is coupled between laser array 208 and photodiode array 216.

[0021] First DSP 202 in the embodiment shown includes a space-time encoder 204 coupled to receive a single data stream 200. Space-time encoder may perform a space-time encoding algorithm on the data received from single data stream 200. The space-time encoding algorithm may be one that is known from the art of wireless communications, and may include a space-time trellis code or a space-time block code. The space-time code may also take into account channel impairments.

[0022] The encoded information generated by space-time encoder 204 may be received in the form of electrical signals by adaptive modulation unit 206, which may perform an adaptive modulation algorithm. The adaptive modulation algorithm performed may match the modulation of the electrical signals to conditions in the optical link, which may be referred to as channel characteristics. The adaptively modulated electrical signals may be provided from adaptive modulation unit 206 to the lasers of laser array 208. Active lasers of laser array 208 may convert the received electrical signals into optical signals that are transmitted across multi-mode fiber 212. The modulation performed by adaptive modulation unit 206 may include one of a number of different modulation schemes, such as quadrature amplitude modulation (QAM), discrete multi-tone (DMT) modulation, or virtually any other suitable modulation technique. Additional techniques such as orthogonal frequency division multiplexing (OFDM) may also be employed by the communications system.

[0023] The transmitted optical signals may be received at the other end of multi-mode fiber 212 by photodiodes of photodiode array 216. Each photodiode may convert received optical signals into electrical signals that may then be forwarded to dispersion compensation unit 222. Dispersion compensation unit 222 may utilize one or more NxM channel estimation matrices, which may include estimates of channel characteristics obtained during performance of a training algorithm. It is noted that N is the number of

transmitters (e.g., lasers) operating while M is the number of receivers (e.g., photodiodes) operating, and these numbers may be different from one another. The channel estimation matrices may be used by dispersion compensation unit 222 to produce inverse channel estimation matrices that can be combined with the electrical signals to compensate for optical dispersion in the channel, and thus recover the electrical signals in a form such as that of the electrical signals that were provided to laser array 208 by adaptive modulation unit 206. The electrical signals recovered by dispersion unit 222 may then be provided to space-time decoder 220, which performs a space-time decoding operation to recover the original data stream. The original data stream may then be output from DSP 218.

[0024] Fig. 3 further illustrates the use of adaptive modulation. In the embodiment shown, the communications system includes a first communications link across multi-mode fiber 306 and a second communications link across multi-mode fiber 322. A first transmitter includes DSP 300 and laser array 302, while a second transmitter includes DSP 314 and laser array 318. A first receiver includes photodiode array 310 and DSP 312, while a second receiver includes DSP 330 and photodiode array 326. DSP 312 is coupled to provide adaptive modulation data to DSP 314, while DSP 330 is coupled to provide adaptive modulation data to DSP 300. Although not explicitly shown here, DSP 300 and DSP 314 may each include an adaptive modulation unit 206, as discussed above with reference to Fig. 2.

[0025] In the embodiment shown, channel characteristics (e.g., temperature, micro-vibration effects, etc.) for the first communications link may be determined by DSP 312. Information indicative of channel characteristics for the first communications link may be provided to DSP 314, transmitted over the second communications link to DSP 330, and provided back to DSP 300. For subsequent transmissions, DSP 300 may use the received adaptive modulation data to perform an adaptive modulation algorithm on electrical signals that are to be converted to optical signals and transmitted across the first data link. The adaptive modulation algorithm performed may compensate signals, prior to transmission, for the conditions on the communications link, such that they arrive at a receiver in a condition that is closer to the intended form than they otherwise would if uncompensated.

[0026] For the second communications link, adaptive modulation information may be conveyed in a similar manner. DSP 330 may determine channel characteristics for the second communications link and convey this information to DSP 300. The information may be transmitted across the first communications link to DSP 312 and be subsequently conveyed to DSP 314. In subsequent transmissions, DSP 314 may use its received adaptive modulation data in the performance of an adaptive modulation algorithm on data to be transmitted over the second link.

[0027] It is noted that the determination of channel characteristics and the generation and conveyance of corresponding adaptive modulation data may be periodically repeated. Repeating this the generation and

conveyance of adaptive modulation may allow the communications system to respond to changing conditions that can in turn change the channel characteristics for the communications links.

[0028] It is further noted that embodiments are possible and contemplated wherein the adaptive modulation information is conveyed by means other than the optical communications links shown. For example, one embodiment is possible and contemplated where a dedicated wired or wireless electrical link exists between DSP 312 and DSP 300 to convey adaptive modulation information from the receive side of the first communications link to the corresponding transmit side.

[0029] Fig. 4 illustrates a flow diagram for one embodiment of a method for optimizing modal coupling diversity in an optical communications system. Modal coupling diversity may be used with optical communications system that use multiple optical transmission devices (e.g., lasers) that operate on a thermal budget (i.e. within or under a thermal threshold). Due to the low costs of optical transmitters and receivers that may be used with multi-mode fiber, it may be more economical to include a greater number of each in an optical communications system. This may lead to excess capacity that may exceed thermal constraints were all transmitters to be operated at the same time. The method for optimizing modal coupling diversity may include selecting a subset of these transmitters that may operate within the established thermal constraints of the system while maximizing modal coupling diversity relative to other possible subsets.

[0030] Modal coupling diversity optimization may take advantage of the fact that there are many different paths for light to travel in a multi-mode fiber. The various paths traveled by different light rays within a multi-mode fiber may result in different modal coupling characteristics on the receive side. By increasing the variation of modal coupling characteristics (i.e. maximizing modal coupling diversity), the likelihood that information transmitted through the fiber on multiple modes is successfully recovered at the receive side.

[0031] The method shown in Fig. 4 begins with a determination of a thermal budget available to the lasers in a laser array of an optical communications system (block 402). This may include measuring temperatures around a transceiver and determining a portion of an overall thermal budget that is to be allocated to the laser array. After determining the thermal budget for the laser array, a determination can be made of the number of lasers that may be operated simultaneously without exceeding the portion of the thermal budget allocated to the laser array.

[0032] With the number of lasers that can be operated within the specified thermal constraints being established, the method may iterate through the laser array, performing sample transmissions by each laser

and measuring corresponding modal coupling characteristics seen on the receive side (block 406). Based on the measured modal coupling characteristics, lasers of the array may be selected to form a subset of lasers having the largest modal coupling diversity relative to other possible subsets (block 408) while remaining within the specified thermal constraints. The lasers of the subset may be enabled for subsequent operations, while the other lasers may be disabled (block 410). The enabled lasers may then transmit optical signals over the multi-mode fiber (block 412). The method may be periodically repeated to adapt to changing conditions (e.g., changing temperatures at the transceiver; block 416).

[0033] The method illustrated in Fig. 5 is similar to that illustrated in Fig. 4. The allocation of a portion of the thermal budget available to lasers of a laser array and the determination of the number of lasers that may be simultaneously operated may be performed a single time. The other portions of the method (blocks 506, 508, etc.) are analogous to similar portions (e.g., blocks 406, 408, etc.) in the block of the method of Fig. 4. Accordingly, the primary difference between these two methodologies is that the thermal budget allocated to the laser array is a static (one-time) calculation in the method shown in Fig. 5, while it is a dynamic (each method iteration) calculation in the method shown in Fig. 4. Furthermore, in this particular embodiment, electrically signals provided to the lasers are adaptively modulated prior to conversion to optical signals and subsequent transmission (block 512). Adaptive modulation may also be implemented in the embodiment of Fig. 4. However, adaptive modulation is not a requirement for either of these embodiments.

[0034] Fig. 6A illustrates a 3x3 array of vertical cavity surface emitting lasers (VCSELs), while Fig. 6B illustrates a subset of lasers that may be selected, in one instance, from performance of an embodiment of the modal coupling diversity optimization methods described above. The selected lasers comprising the subset are shown in white, while those lasers that are disabled are shown in black. In Fig. 6C, numerical values indicating the portion of the allocated thermal budget consumed by each laser is shown. For example, the laser in the upper left hand corner consumes 32% of the allocated thermal budget in this example, while the laser in the lower middle block consumes 15%. More particularly, in Fig. 6C, the thermal design power (TDP) has been reallocated such that some lasers use more power than others to maximize modal coupling diversity.

[0035] Fig. 7A illustrates another laser array in which the middle row of VCSELs is horizontally offset with respect to the top and bottom rows. Fig. 7B illustrates the selected subset and the disabled subset in one instance, with each selected VCSEL being represented by the white blocks. Fig. 7C illustrates the amount of the allocated thermal budget consumed by each VCSEL of the selected subset. Similar to the arrangement shown in Fig. 6C, TDP has been reallocated such that some of the lasers use more power than the others in order to maximize modal coupling diversity.

[0036] Fig. 8 illustrates another example wherein lasers may be rotated and/or moved in position to further increase modal coupling diversity.

[0037] It is noted that the various embodiments discussed herein and shown in the accompanying drawings are exemplary. Many other embodiments, not explicitly disclosed herein, are possible and contemplated within the spirit and scope of this disclosure.

WHAT IS CLAIMED IS:

1. An optical communications system comprising:
one or more optical-to-electrical (OE) converters (216) coupled to receive optical signals from a multi-mode optical fiber (212) and configured to convert the received optical signals into corresponding electrical signals; and
a first digital signal processor (DSP) (218) coupled to receive electrical signals from the one or more OE converters, wherein the first DSP is configured to perform a dispersion compensation algorithm on the received electrical signals.
2. The optical communications system as recited in claim 1, wherein the communications system further includes:
one or more optical transmission devices (208) coupled to drive optical signals into a first end of the multi-mode optical fiber; and
a second DSP (202) configured to receive a data stream and further configured to provide, to each of the one or more optical transmission devices, electrical signals corresponding to data in the data stream.
3. The optical communications system as recited in claim 2, wherein the second DSP includes space-time encoder (204) coupled to receive the data stream and configured to perform a space-time encoding algorithm on the data in the data stream.
4. The optical communications system as recited in claim 2, wherein the second DSP includes an adaptive modulation unit (206) coupled to receive one or more encoded signals from the space-time encoder, wherein the adaptive modulation unit is configured to modulate the encoded signals based on one or more channel characteristics, and wherein the adaptive modulation unit is configured to provide one or more modulated signals to the one or more optical transmission devices.
5. The optical communications system as recited in claim 4, wherein the adaptive modulation unit (206) is further coupled to receive channel characteristic information from a third DSP (330), wherein the third DSP is coupled to receive electrical signals from one or more of a corresponding plurality of OE converters (326).
6. The optical communications system as recited in claim 1, wherein the optical communications system includes a plurality of optical transmission devices (208), wherein the optical communications system is configured to, during operation, activate a subset of the plurality of

optical transmission devices based on a maximum modal coupling diversity value determined by performing a training algorithm.

7. The optical communications system as recited in claim 1, wherein the multi-mode optical fiber has a length greater than 2 kilometers.
8. The optical communications system as recited in claim 1, wherein the first DSP includes a dispersion compensation unit (222) coupled to receive the electrical signals output from the one or more OE converters, wherein the dispersion compensation unit is configured to generate one or more compensated signals by applying one or more channel estimation matrices to the electrical signals, the channel estimation matrices being based on characteristics of corresponding channels.
9. The optical communications system as recited in claim 1, wherein the first DSP includes a space-time decoder (220) coupled to receive the one or more compensated signals to a space-time decoder, wherein the space-time decoder is configured to re-generate the data stream by performing a space-time decoding algorithm on the one or more compensated signals.
10. An optical communications system comprising:
 - a first digital signal processor (DSP) (202) configured to receive a data stream and further configured to perform an adaptive modulation algorithm on a first set of electrical signals in order to generate a second set of electrical signals, wherein the first set of electrical signals corresponds to data in the data stream, and wherein the second set of electrical signals is generated by the adaptive modulation algorithm shaping each of the first set of electrical signals based on one or more channel characteristics; and
 - one or more optical transmission devices (208) coupled to receive the second set of electrical signals and configured to convert the electrical signals into optical signals and to drive the optical signals into a first end of a multi-mode optical fiber.
11. The optical communications system as recited in claim 10, further comprising:
 - one or more optical-to-electrical (OE) converters (216) coupled to receive optical signals from a second end of the multi-mode optical fiber and configured to convert the received optical signals into corresponding electrical signals; and
 - a second DSP (218) coupled to receive electrical signals from the one or more OE converters, wherein the second DSP is configured to perform a dispersion compensation algorithm on the received electrical signals.

12. The optical communications system as recited in claim 10, wherein the optical communications system includes a plurality of optical transmission devices (208), wherein the optical communications system is configured to, during operation, activate a subset of the plurality of optical transmission devices based on a maximum modal coupling diversity value determined by performing a training algorithm.
13. A method (400) comprising:
calculating (404) how many of a plurality optical transmission devices (208) can be concurrently operated without exceeding a thermal threshold;
selecting (408) a subset of the of the plurality of optical transmission devices, wherein selecting the subset includes selecting particular ones of the plurality of optical transmission devices having a maximum modal coupling diversity value without exceeding the thermal threshold; and
transmitting optical signals onto a multi-mode optical fiber using the subset of optical transmission devices.
14. The method as recited in claim 13, further comprising periodically repeating (416) said calculating, and said selecting the subset.
15. The method as recited in claim 13, further comprising adaptively modulating (512) electrical signals provided to each of the subset of optical transmission devices based on one or more channel characteristics.
16. The method as recited in claim 13, further comprising determining the maximum modal coupling diversity (408) based on modal coupling characteristics determined at a receiver coupled to receive optical signals transmitted across a multi-mode fiber by each of the plurality of optical transmission devices.
17. The method as recited in claim 13, wherein determining the maximum modal coupling diversity (408) comprises determining modal coupling characteristics for each of the plurality of optical transmission devices.
18. The method as recited 13, further comprising periodically determining the thermal threshold (402) for the plurality of optical transmission devices in a transmitter unit of an optical communications system.
19. The method as recited in claim 13, further comprising:

a plurality of opto-electronic (OE) converters receiving optical signals from the multi-mode fiber
and converting the optical signals into electrical signals;
performing a dispersion compensation algorithm on the electrical signals.

20. The method as recited in claim 13, further comprising allocating power among the subset of optical transmission devices to obtain maximum mobile coupling diversity.

1 / 8

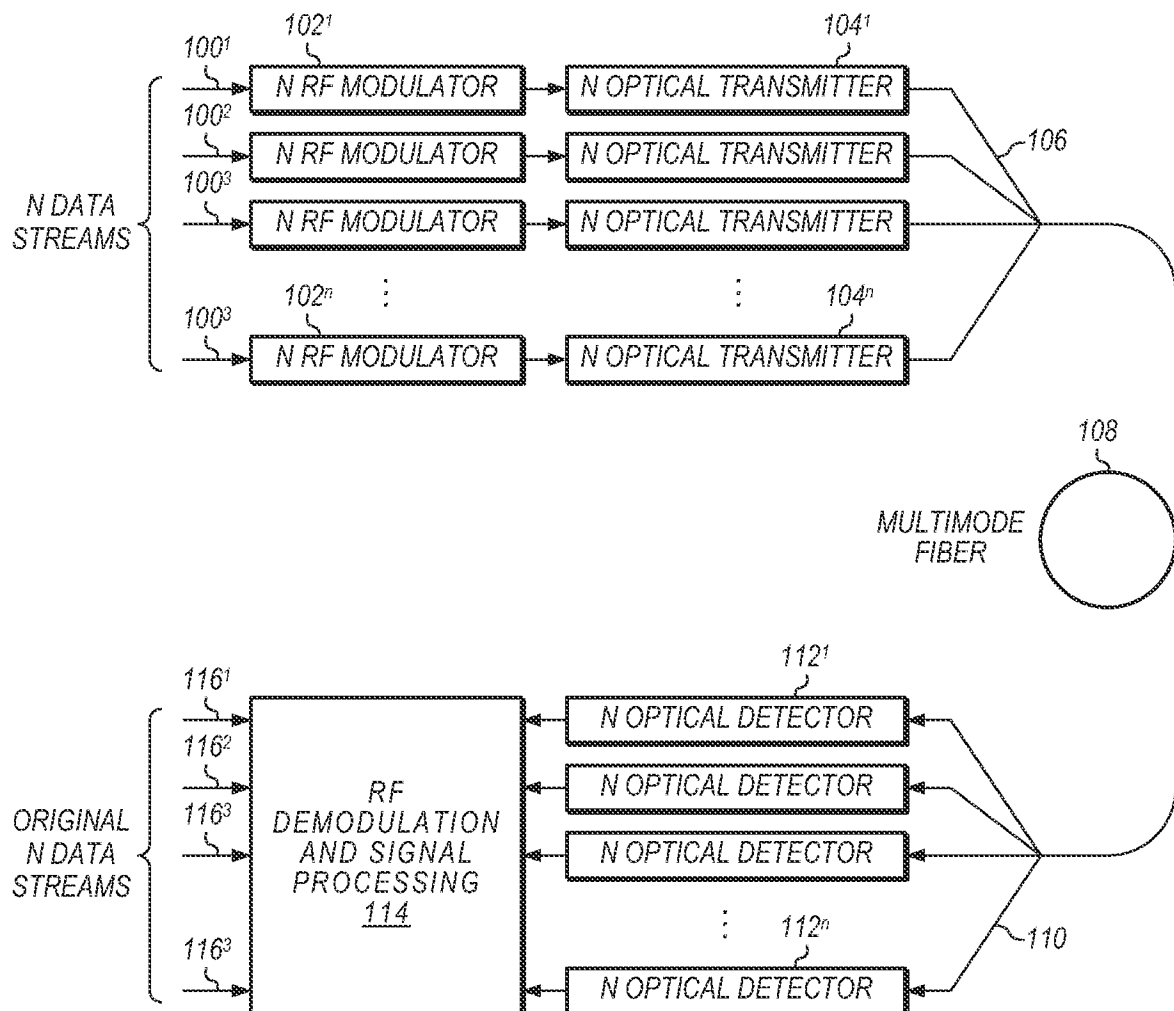


FIG. 1

2 / 8

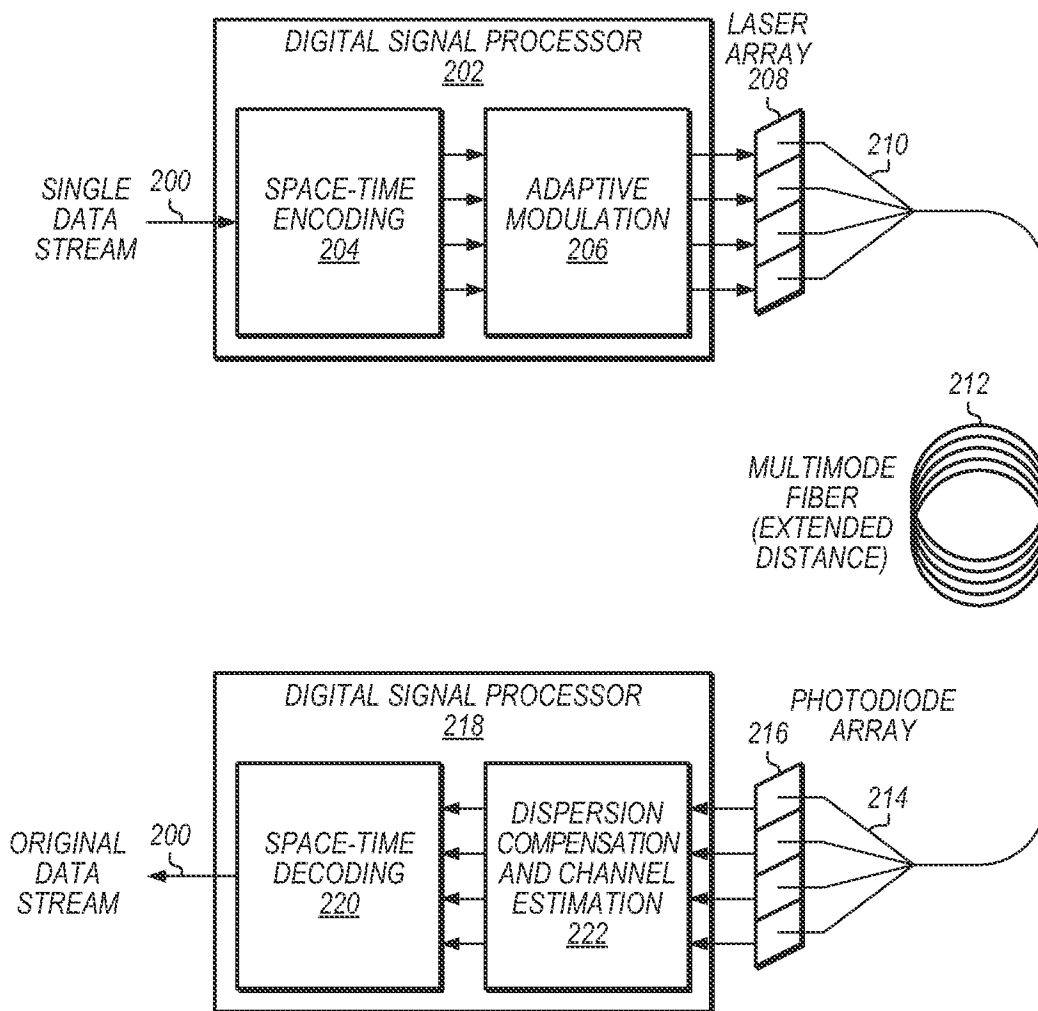


FIG. 2

3 / 8

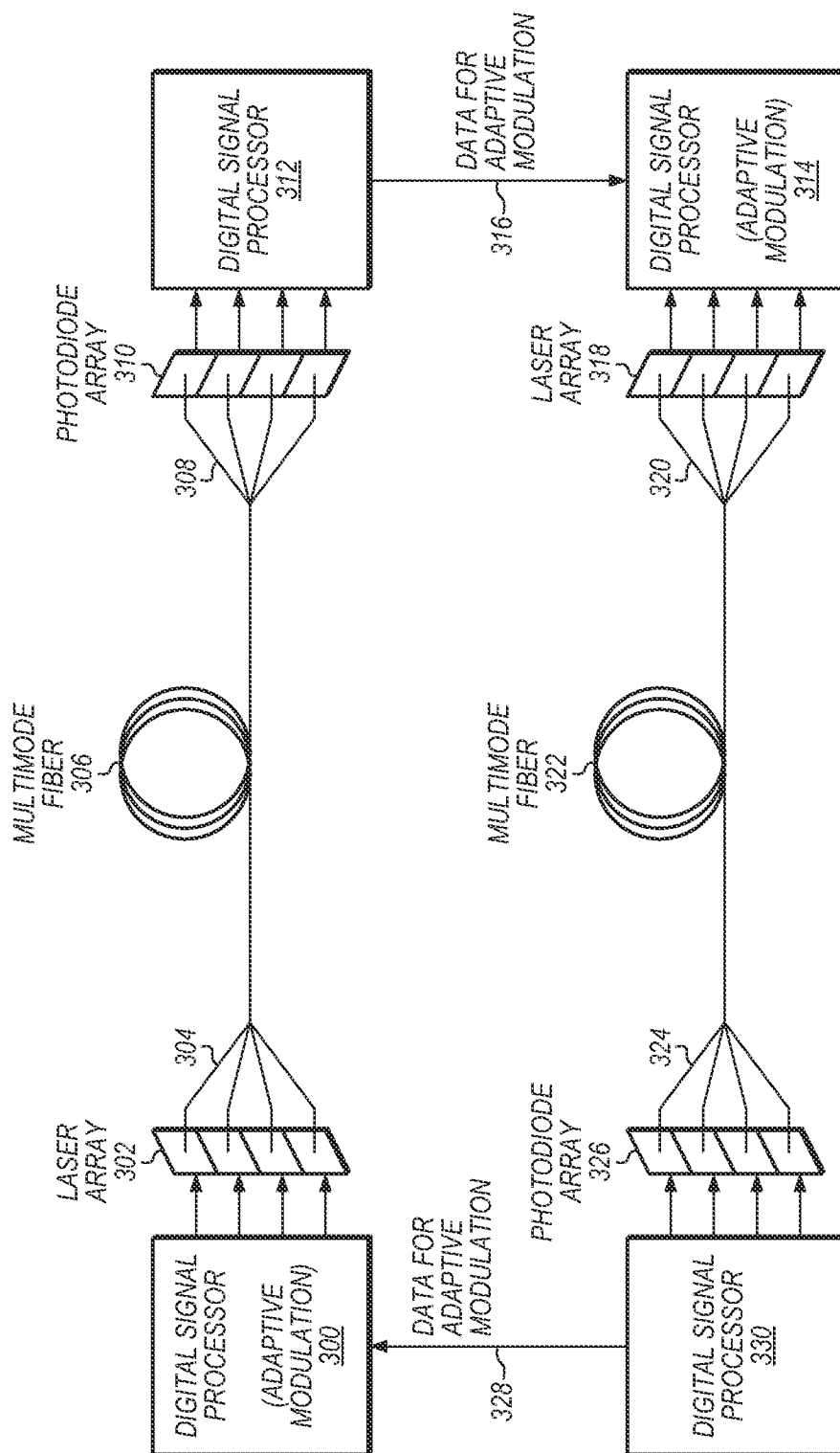


FIG. 3

4 / 8

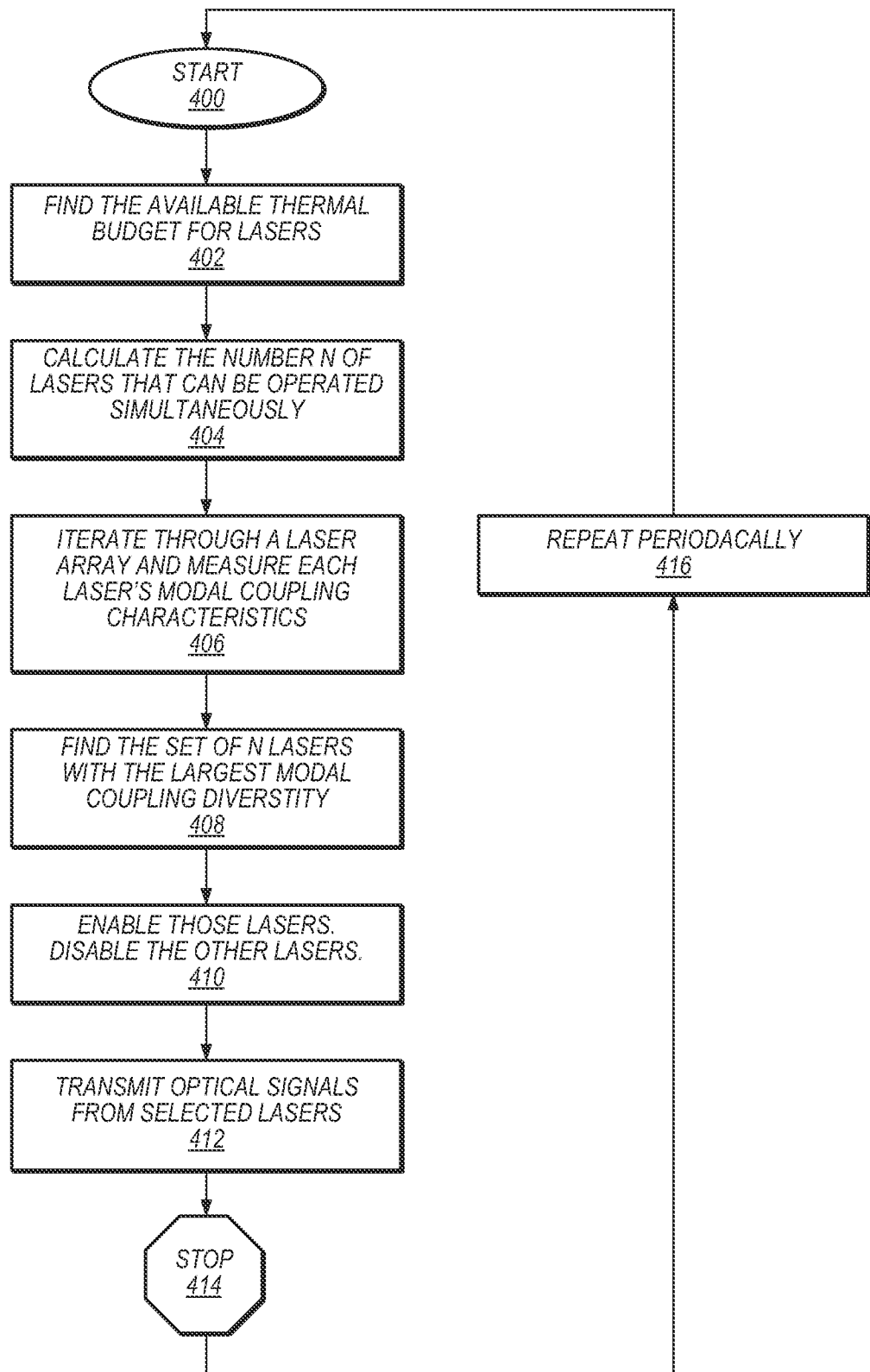


FIG. 4

5 / 8

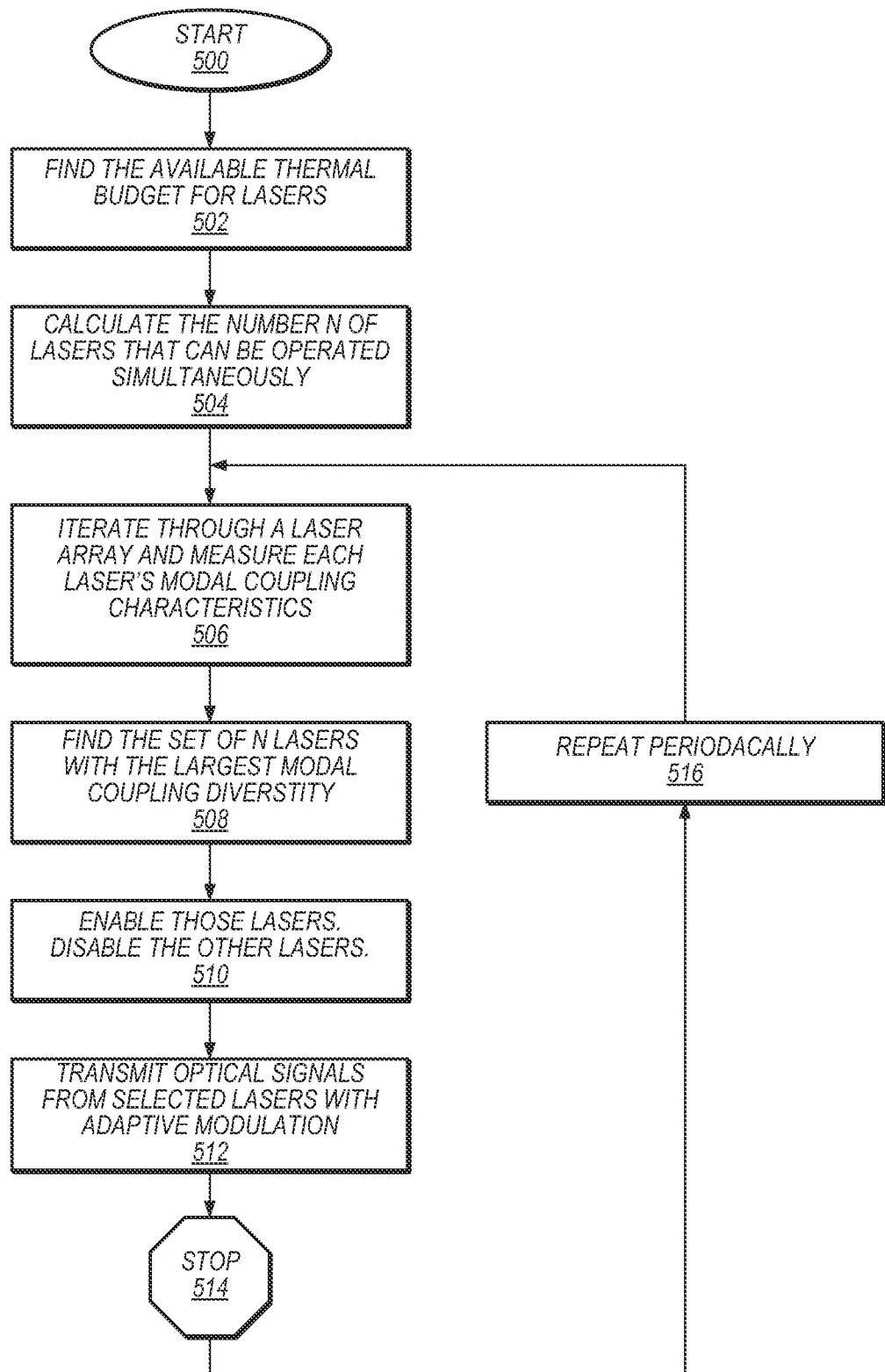


FIG. 5

VCSEL	VCSEL	VCSEL
VCSEL	VCSEL	VCSEL
VCSEL	VCSEL	VCSEL

FIG. 6A

FIG. 6B

32%		
8%		29%
	15%	16%

FIG. 6C

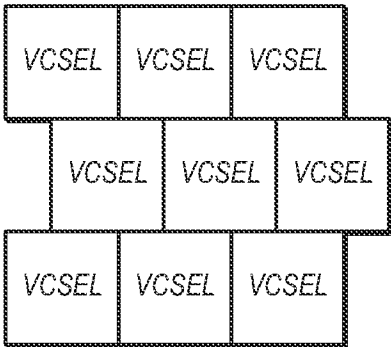


FIG. 7A

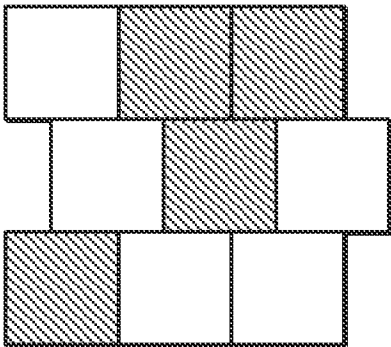


FIG. 7B

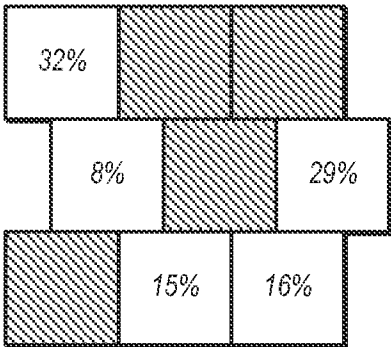


FIG. 7C

8 / 8

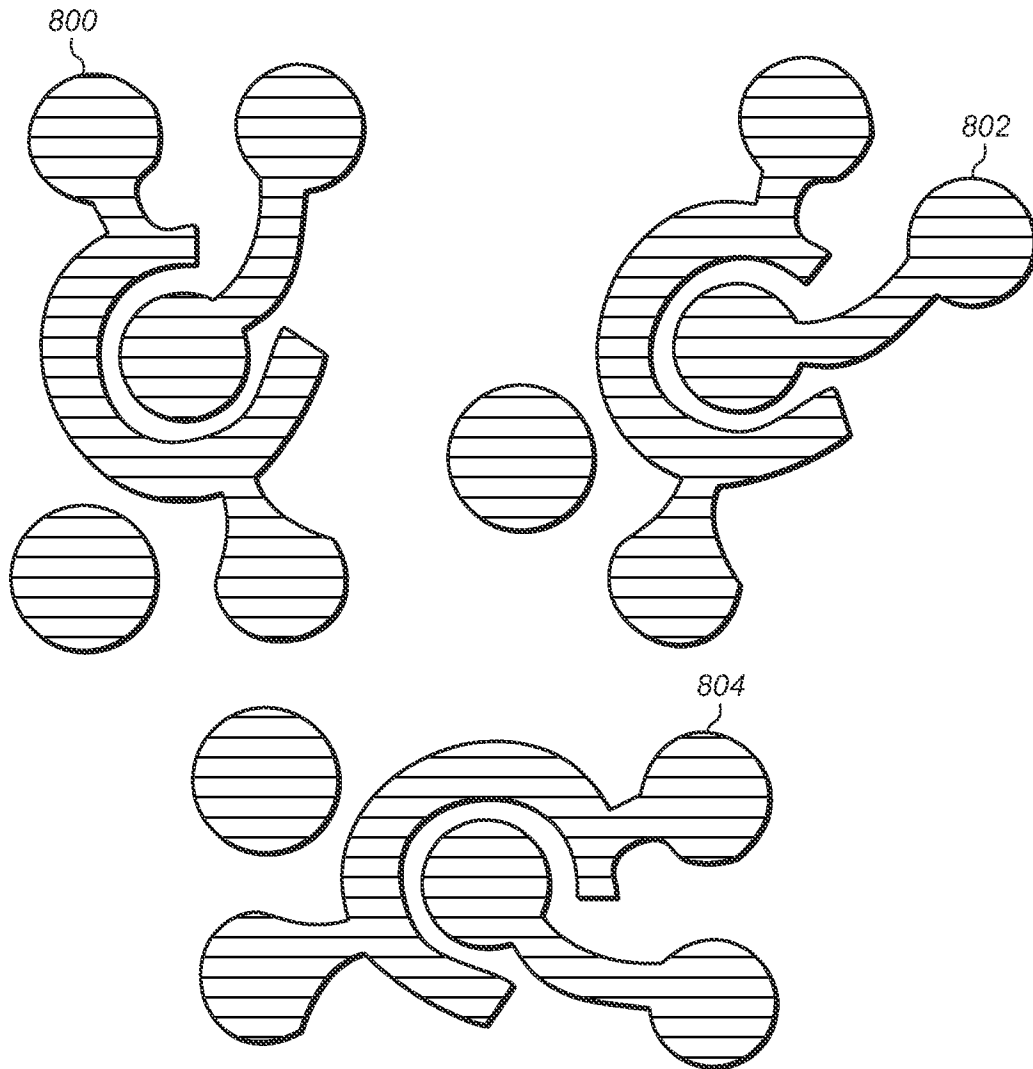


FIG. 8